

Parity Mixed Doublets in $A = 36$ Nuclei

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Abstract

The γ -circular polarizations (P_γ) and asymmetries (A_γ) of the parity forbidden M1 + E2 γ -decays: $^{36}\text{Cl}^*(J^\pi = 2^-; T = 1; E_x = 1.95 \text{ MeV}) \rightarrow ^{36}\text{Cl}(J^\pi = 2^+; T = 1; g.s.)$ and $^{36}\text{Ar}^*(J^\pi = 2^-; T = 0; E_x = 4.97 \text{ MeV}) \rightarrow ^{36}\text{Ar}^*(J^\pi = 2^+; T = 0; E_x = 1.97 \text{ MeV})$ are investigated theoretically. We use the recently proposed Warburton-Becker-Brown shell-model interaction. For the weak forces we discuss comparatively different weak interaction models based on different assumptions for evaluating the weak meson-hadron coupling constants. The results determine a range of P_γ values from which we find the most probable values: $P_\gamma = 1.1 \cdot 10^{-4}$ for ^{36}Cl and $P_\gamma = 3.5 \cdot 10^{-4}$ for ^{36}Ar .

PACS numbers: 21.60.Cs, 24.80.-x, 27.30.+t, 12.15.Ji

Parity nonconservation (PNC) in the nucleon-nucleon interaction has been observed in the left-right asymmetry in $\vec{p} - p$ scattering [1], in nucleon-nucleus scattering induced by polarized projectiles (such as \vec{p} [2] or \vec{n} [3]) in spontaneous α -decay [4], [5] and in the circular polarization [6] [7], [8] or asymmetry [9], [10], [11], [12] (from polarized nuclei) of the radiation emitted in nuclear γ -decay. There are also theoretical predictions for new PNC experiments in induced α -decay [13], [14] and asymmetry of the radiation emitted in nuclear γ -decay [15], [16]. The theoretical and experimental work in this field has been reviewed recently [11], [12], [17].

The controversy [11], [12], [18], [19], [20] in calculating weak meson-nucleon coupling constants in nuclei has greatly stimulated the investigation of possible experiments sensitive to different components of the PNC interaction Hamiltonian (H_{PNC}), that depend linearly on seven such weak coupling constants: $h_{meson}^{\Delta T}$: h_{π}^1 , h_{ρ}^0 , h_{ρ}^1 , h_{ρ}^2 , $h_{\rho'}^1$, h_{ω}^0 , h_{ω}^1 . Various linear combinations of these constants can, in principle, be extracted in different experiments, and among these are those for the parity mixed doublets (PMD) [11], [16]. The most interesting PMD cases are those for which the PNC effect is enhanced due to a small energy difference between the two states and due to a favourable ratio of the transition probabilities. Since the PMD has definite isospins, the transition "filters out" specific isospin components of PNC weak interaction.

In the present paper a theoretical investigation of two new PMD cases in nuclei with $A=36$ is presented. The first one, in ^{36}Cl , is given by the $J^{\pi}T = 2^{-1}$, $E_x=1.951$ MeV and $J^{\pi}T = 2^{+1}$, $E_x=1.959$ MeV levels (see Fig. 1). The second one, in ^{36}Ar , is given by the $J^{\pi}T = 2^{-0}$, $E_x=4.974$ MeV and $J^{\pi}T = 2^{+0}$, $E_x=4.951$ MeV levels (see Fig. 2). In order to have an amplification of the PNC effect we look to the suppressed transitions from the $J^{\pi}T = 2^{-1}$ levels to the $J^{\pi}T = 2^{+1}$ ground state for ^{36}Cl and from $J^{\pi}T = 2^{-0}$ level to the $J^{\pi}T = 2^{+0}$, $E_x=1.97$ MeV, level for ^{36}Ar . The corresponding PNC matrix elements were calculated with the shell-model code OXBASH, with the Warburton-Becker-Brown interaction [22] for $2s1d-2p1f$ model space. One of the cases considered here (^{36}Cl) has been

investigated previously [15] with a much smaller valence model space which included only the $1d_{\frac{3}{2}}$ and $1f_{\frac{7}{2}}$ orbitals. Within this $(1d_{\frac{3}{2}}, 1f_{\frac{7}{2}})$ small model space the one-body contribution to the PNC matrix element between the members of the doublet (M_{PNC}) vanishes. Within the present model space the contribution of the one-body term dominates the theoretical M_{PNC} . The goal of the present work is to calculate the PNC γ asymmetries and circular polarizations of the proposed gamma ray transitions within different weak-interaction models in order judge the experimental feasibility.

The degree of circular polarization of the emitted γ -rays is given (see Ref. [23] chapter 9, § 3 eq. (9.38)) by a sum of parity nonconserving (PNC) and parity conserving (PC) contributions:

$$P_{\gamma}(\cos \theta) \equiv \frac{W_{right}(\theta) - W_{left}(\theta)}{W_{right}(\theta) + W_{left}(\theta)} = (P_{\gamma})_0 \cdot R_{\gamma}^{PNC}(\cos \theta) + R_{\gamma}^{PC}(\cos \theta), \quad (1)$$

where R_{γ}^{PC} is a parity conserving quantity discussed bellow,

$$(P_{\gamma})_0 = 2 \cdot \frac{M_{PNC}}{\Delta E} \sqrt{\frac{b_+ \cdot \tau_-}{b_- \cdot \tau_+}} \cdot \left(\frac{E_{\gamma}^-}{E_{\gamma}^+} \right)^3 \cdot \sqrt{\frac{1 + \delta_-^2}{1 + \delta_+^2}} \quad (2)$$

and

$$R_{\gamma}^{PNC}(\cos \theta) = \sqrt{\frac{1 + \delta_-^2}{1 + \delta_+^2}} \left\{ \sum_{\nu=0,2,4} P_{\nu}(\cos \theta) B_{\nu}(2) [F_{\nu}(1122) + F_{\nu}(2222) \delta_+ \delta_+ + F_{\nu}(1222)(\delta_- + \delta_+)] \right\} \cdot \left\{ \sum_{\nu=0,2,4} P_{\nu}(\cos \theta) B_{\nu}(2) [F_{\nu}(1122) + F_{\nu}(2222) \delta_-^2 + 2F_{\nu}(1222) \delta_-] \right\}^{-1}. \quad (3)$$

R_{γ}^{PNC} is a multiplier due to the existence of the orientation of the nuclear spin in the initial excited state when the mixing ratios do not vanish. In the above equations, δ_- is the M2/E1 mixing ratio, δ_+ is the E2/M1 mixing ratio, the F_{ν} coefficients are defined by

$$F_{\nu}(LL' I' I) = (-1)^{I' + 3I - 1} [(2I + 1)(2L + 1)(2L' + 1)]^{\frac{1}{2}} C(LL' \nu; 1 - 10) W(LL' II; \nu I'), \quad (4)$$

C is the Clebsch-Gordan coefficient $C(J_1 J_2 J_3; M_1 M_2 M_3)$ and W is the Racah coefficient. The parity conserving (PC) quantity is given by [23]:

$$R_\gamma^{PC}(\cos\theta) = \left\{ \sum_{\nu=1,3} P_\nu(\cos\theta) B_\nu(2) [F_\nu(1122) + F_\nu(2222)\delta_-^2 + 2 \cdot F_\nu(1222)\delta_-] \right\} \cdot \left\{ \sum_{\nu=0,2,4} P_\nu(\cos\theta) B_\nu(2) [F_\nu(1122) + F_\nu(2222)\delta_-^2 + 2F_\nu(1222)\delta_-] \right\}^{-1}, \quad (5)$$

where

$$B_\nu(2) = \sum_M (2\nu + 1)^{\frac{1}{2}} C(2\nu 2; M 0 M) p(M). \quad (6)$$

$p(M)$ is the polarization fraction of the M -state, which determines the degree of the orientation of the nucleus.

In order to measure a PNC effect one must find situations for which the R_γ^{PC} part in Eq. (1) vanishes. Two particular cases have this property: i.) The case of an initially unpolarized nucleus for which $B_0(2) = 1$, $B_{\nu \neq 0}(2) = 0$ and $F_0(LL'22) = \delta_{LL'}$. In this particularly simple case P_γ reduces to the well known expression of the circular polarization, $(P_\gamma)_0$. ii.) One may prepare a polarized state by choosing $p(M) = \delta_{M0}$ for which, $B_{\nu=1,3}(2) = 0$ and R_γ^{PC} part vanishes.

Another observable which measures a PNC effect is the forward-backward asymmetry of the gamma rays emitted by polarized nuclei

$$A_\gamma(\theta) \equiv \frac{W(\theta) - W(\pi - \theta)}{W(\theta) + W(\pi - \theta)}. \quad (7)$$

This observable has been successfully used in the ^{19}F case [9], [10] in order to avoid the small efficiency of the Compton polarimeters when one measures the degree of circular polarization. If the mixing ratios are small ($\delta_+, \delta_- \ll 1$) one can show that [21]

$$A_\gamma(\theta) \simeq (P_\gamma)_0 \cdot R_\gamma^{PC}(\cos\theta), \quad (8)$$

where θ represents the angle between the emitted photon and the axis of polarization (if any). The angular distribution described by this formula has a maximum for $\theta = 0^\circ$ [21]. It has the advantage that the parity conserving (PC) circular polarization, $R_\gamma^{PC}(\theta)$ in Eq. (8), can be measured experimentally. $(P_\gamma)_0$ is the essential quantity for all PNC observable.

In order to determine the magnitude of $(P_\gamma)_0$ we have made a shell-model estimate of the PNC matrix element

$$M_{PNC} = \langle J^\pi T, E_x(\text{MeV}) | H_{PNC} | J^{-\pi} T' E'_x(\text{MeV}) \rangle, \quad (9)$$

where H_{PNC} is the PNC Hamiltonian given by Desplanques, Donoghue and Holstein (DDH) [12], Dubovik and Zenkin (DZ) [18], Adelberger and Haxton (AH) [11] or Kaiser and Meissner (KM) [19].

The calculations were carried out with the shell-model code OXBASH [25] in the $2s1d$ - $2p1f$ model space in which the $2s_{1/2}$, $1d_{5/2}$, $1d_{3/2}$, $2p_{1/2}$, $2p_{3/2}$, $1f_{7/2}$ and $1f_{5/2}$ orbitals are active. The truncations we made within this model space were $(2s1d)^{20} (0\hbar\omega)$ for the positive parity states and $(2s1d)^{19}(2p1f)^1 (1\hbar\omega)$ for the negative parity states. These truncations are necessary due to the dimension limitations, but we believe that they are realistic. The Brown-Wildenthal interaction [26] was used for the positive parity states and the Warburton-Becker-Brown interaction [22] was used for the negative parity states. Both interactions have been tested extensively with regards to their reproduction of spectroscopic properties [22], [26]. The calculation of the PNC matrix element which included both the core (inactive) and active orbitals has been performed as described in Ref. [27].

All the components [12], [11] of the parity nonconserving potential are short range two-body operators. Because the behavior of the shell-model wave functions at small NN distances has to be modified, short range correlations (SRC) were included by multiplying the harmonic oscillator wave functions (with $\hbar\omega = (45 \cdot A^{-\frac{1}{3}} \text{ MeV} - 25 \cdot A^{-\frac{2}{3}} \text{ MeV})$) by the Miller and Spencer factor [28]. This procedure is consistent with results obtained by using more elaborate treatments of SRC such as the generalized Bethe-Goldstone approach [7], [8]. The PNC pion exchange matrix is decreased by 30 to 50% as compared with the values of the matrix elements without including SRC, while the ρ (ω) exchange matrix elements is much smaller (by a factor of $\frac{1}{3}$ to $\frac{1}{6}$).

The calculated excitation energies of the first three T=0, 2^+ levels in ^{36}Ar are 1.927, 4.410 and 7.174 MeV. The first two of these are in good agreement with experimental levels at 1.970 and 4.440 MeV. The third experimental 2^+ state at $E_x=4.951$ MeV (the state belonging to the parity doublet) apparently is an intruder state in the $2s1d$ ($0\hbar\omega$) model space. This

conclusion is also supported by the suppressed Gamow-Teller β transition probability to this third state [29]. We have thus expanded the model space to include some $2\hbar\omega$ configurations - those of the type $(1d_{5/2})^{12}(2s_{1/2}, 1d_{3/2})^6(2p_{3/2}, 1f_{7/2}, 2p_{1/2})^2$. The $2\hbar\omega$ configurations were shifted down by 11.5 MeV relative to the $0\hbar\omega$ configurations so that the first 2^+0 state with a dominant $2\hbar\omega$ component ($\sim 80\%$) becomes the third 2^+ in the calculated $(0+2)\hbar\omega$ spectrum. The dominant PNC transition is $1d_{3/2} - 2p_{3/2}$ and the DDH PNC matrix elements is 0.12 eV (see Table 1). Due to the truncations made, the PNC result for ^{36}Ar may not be as reliable as that for ^{36}Cl .

The calculated excitation energies of the first three $T=1$, 2^+ levels in ^{36}Cl are 0, 2.008, 2.451 and 4.429 MeV. The first three of these are in good agreement with experimental levels at 0, 1.959 and 2.492 MeV. The theoretical B(E2) and B(M1) and mixing ratios are in relatively good agreement with the experiment (see Table 1). For both ^{36}Ar and ^{36}Cl the 2^- states are the lowest observed experimentally and the theoretical wave functions should thus be fairly reliable. The extremely weak E1 transitions do not serve as a useful test of the wave functions (the one in ^{36}Ar is isospin forbidden).

DDH [12] investigated a variety of approximations within the quark model for the weak coupling constants and discussed the model uncertainties. These uncertainties give rise to a range of values for the PNC coupling constants. Recently several other calculations have been made, one within the framework of the chiral soliton model [19] and others within the quark framework [18], [20]. Even though both of these approaches lead to fixed values for PNC coupling constants [19] (see Table 2), the values are subject to uncertainties. In particular, the soliton model gives an extremely small value for h_π as compared to DDH, however, this result comes essentially from the factorization approximation, and DDH discuss the importance of going beyond the factorization approximation [12]. In any case it is clear that the observation of PNC in nuclei is a test not only of the Δ -S=0 PNC component of the weak interaction, but also of the hadronic strong interaction models.

The results (up to a complex phase factor) can be summarized as:

$$M_{PNC}(^{36}\text{Cl}) = (1.09 \cdot h_{\pi}^1 - 0.20 \cdot h_{\rho}^1 - 0.30 \cdot h_{\omega}^1 - 0.027 \cdot h_{\rho'}^1 + 0.57 \cdot h_{\rho}^0 + 0.32 \cdot h_{\omega}^0 + 0.015 \cdot h_{\rho}^2) \cdot 10^{-2} \text{eV}, \quad (10)$$

and

$$M_{PNC}(^{36}\text{Ar}) = -(1.00 \cdot h_{\rho}^0 + 0.44 \cdot h_{\omega}^0) \cdot 10^{-2} \text{eV}. \quad (11)$$

Here $h_{meson}^{\Delta T}$ should be given in units of 10^{-7} as in Table 2.

In the ^{36}Cl case the components containing h_{π} (M_{π}) and $h_{\rho(\omega)}$ ($M_{\rho+\omega}$) couplings come in with opposite signs, however the difference is remarkably almost the same in all the weak interaction models. The specific numbers are: $M_{\pi} = 0.050$ eV and $M_{\rho+\omega} = -0.069$ eV for DDH, and $M_{\pi} = 0.00207$ eV and $M_{\rho+\omega} = -0.023$ eV for KM. In the ^{36}Ar case the h_{ρ} -components strongly dominate the PNC matrix element (M_{PNC}) (e.g. within DDH: $M_{\rho} = 0.113$ eV, while $M_{\omega} = 0.009$ eV).

The PNC matrix elements obtained are a factor of 3 - 6 smaller than the typical "isoscalar" matrix elements in A=14-20 nuclei (e.g. ~ 0.3 eV in ^{19}F [11] and ^{14}N [32]). A analysis of the different contributions to the PNC matrix elements indicates the reasons for this behavior:

i.) The one body transition densities (OBTD) for the isoscalar and isovector $1d_{3/2} - 2p_{3/2}$, $2s_{1/2} - 2p_{1/2}$, $1d_{5/2} - 1f_{5/2}$ PNC transitions are a factor 5-10 smaller than the dominant $1p_{1/2} - 2s_{1/2}$ transition in the A=14-20 nuclei. This can be understood by the fact that for A=36 nuclei the most probable subshell to be filled in the $1f2p$ major shell is $1f_{7/2}$ which is 2 MeV lower than $2p_{3/2}$. This substantially decreases the occupation probability of the $2p_{3/2}$ $2p_{1/2}$ and $1f_{5/2}$ states which are important for PNC transitions. In the A=14-20 region the $2s_{1/2}$ is nearly degenerate with the $1d_{5/2}$ state and has a higher occupation probability. In the ^{36}Cl case the dominant OBTD is for the transition $1d_{3/2} - 2p_{3/2}$. We have estimated the $2\hbar\omega - 1\hbar\omega$ and $2\hbar\omega - 3\hbar\omega$ contribution to this dominant transition within the $(2s_{1/2}, 1d_{3/2}, 2p_{3/2}, 1f_{7/2})^8$ mode space. The $2\hbar\omega - 1\hbar\omega$ and $2\hbar\omega - 3\hbar\omega$ contribution have a magnitude of 5 - 7 % of the $0\hbar\omega - 1\hbar\omega$ and are opposite in sign, so they are small and also

cancel each other. These calculations suggest that the $0\hbar\omega - 1\hbar\omega$ contribution is the dominant term. This behaviour is in contrast with that in A=18-21 nuclei, for which the higher $n\hbar\omega$ contributions seems to be important [33]. One can understand this by the relatively weaker coupling between the sd and fp shells as compared with the coupling between the p and sd shells.

ii.) In the case of ^{36}Cl , the isoscalar and isovector contributions have opposite signs leading to a large suppression of the total PNC matrix element (for the DDH weak coupling constants). Considering the strong constraints on h_π^1 given by the ^{18}F experiments, i.e. $h_\pi^1 \leq (1/4)(h_\pi^1)_{DDH}$ [34], one obtains for $(M_{PNC}^{36Cl})_{DDH'}$ a value of -0.057 eV.

Taking into account the results of the above discussion, we have used $M_{PNC}^{36Cl} = -0.057$ eV and $M_{PNC}^{36Ar} = 0.122$ eV to calculate the $(P_\gamma)_0$. We obtain $(P_\gamma)_0^{36Cl} = 1.1 \cdot 10^{-4}$ and $(P_\gamma)_0^{36Ar} = 3.5 \cdot 10^{-4}$ (we used the small mixing ratios, which agree with our calculations). These values can be favorably compared with the experimental upper limit, $P_\gamma \leq 3.9 \cdot 10^{-4}$, for ^{18}F [34].

One can try to avoid the low efficiency of the Compton polarimeters by measuring the forward-backward asymmetry, Eqs. (7), (8). In this case one must find an efficient polarization transfer mechanism which would permit one to obtain a PC circular polarization R_γ^{PC} larger than the polarimeter efficiency ($\sim 1\%$ [11]). For example, the ^{36}Ar PMD can be populated in the $^{39}\text{K}(\vec{p}, \alpha)^{36}\text{Ar}$ reaction (in analogy with the ^{19}F case [9], [10]), with low energy ($E_p \geq 3.7$ MeV) protons, while the ^{36}Cl PMD can be populated in the $^{39}\text{K}(\vec{n}, \alpha)^{36}\text{Cl}$ reaction with relatively slow ($E_n \geq 0.6$ MeV) neutrons.

In conclusion, we have theoretically analyzed two new PMD cases in mass A=36 nuclei. The parity nonconserving transition for the PMD in ^{36}Ar is isoscalar and the corresponding PNC observable is sensitive to the dominant h_ρ^0 weak coupling constant, analogous to the $0^+1, 0^-1$ doublet in ^{14}N [32]. The parity nonconserving transition for the PMD in ^{36}Cl is isoscalar+isovector and the corresponding PNC observable is sensitive to the combination of h_ρ^0 and h_π^1 . From this point of view it is analogous to the ^{19}F case. However, the possi-

ble informations extracted from this case could be complementary to the ^{19}F result. Here, the isoscalar and isovector contributions are out of phase, while for ^{19}F they are in phase. The predicted circular polarizations of the order of magnitude 10^{-4} are within the limits of accuracy of the existent experimental setups.

Acknowledgments

The author would like to thank Drs. B. Alex Brown and O. Dumitrescu for very useful discussions during the preparation of the manuscript. He want to acknowledge support from the Alexander von Humboldt Foundation and NSF grant 94-03666. He also thanks Soros Foundation, Bucharest, Romania for a travel grant.

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Table captions

Table 1 Input data, physical quantities and theoretical PNC matrix elements necessary for calculating γ - circular polarizations and asymmetries for the two PMD - cases studied in the present work. The experimental data is taken from Ref. [30] unless noted.

Table 2 Weak meson - nucleon coupling constants calculated within different weak interaction models (in units of 10^{-7}). The abbreviations are: KM = Kaiser and Meissner [19], DDH = Desplanques, Donoghue and Holstein [12], AH = Adelberger and Haxton [11] and DZ = Dubovik and Zenkin [18]. The g_{meson} needed to obtain these results are were taken from Ref. [11].

Figure captions

Figure 1 Experimentally and theoretically calculated energies for the low $2^{\pm 1}$ levels in ^{36}Cl . The first excited 2^+1 level has been artificially drawn 8 keV higher in order that the PMD to be seen.

Figure 2 Same as Figure 1 for the low $2^{\pm 0}$ levels in ^{36}Ar .

	^{36}Cl	^{36}Ar
$I_i^\pi T_i, E_i(\text{MeV}) \rightarrow$ $I_f^\pi T_f, E_f(\text{MeV})$	$2^+1, 1.959\text{MeV} \rightarrow$ $2^+1, g.s.$	$2^+0, 4.951\text{MeV} \rightarrow$ $2^+0, 1.97\text{MeV}$
life time (τ_+)	60 ± 15 fs	≤ 50 fs
branching ratio (b_+)	94.4 %	15 %
mixing ratio $(\delta_+)_{exp}$	(-5.2 ± 1.6) or (-0.19 ± 0.06) [31]	
mixing ratio $(\delta_+)_{theo}$	-0.24	0.41
$B(\text{M1})_{exp} \mu_N^2$	$0.08 (\delta_+ = -0.2); 0.003 (\delta_+ = -5.2)$	
$B(\text{M1})_{theo} \mu_N^2$	0.14	0.0009
$B(\text{E2})_{exp} \text{e}^2 \text{fm}^4$	$12 (\delta_+ = -0.2); 298 (\delta_+ = -5.2)$	
$B(\text{E2})_{theo} \text{e}^2 \text{fm}^4$	30	0.27
$I_i^\pi T_i, E_i(\text{MeV}) \rightarrow$ $I_f^\pi T_f, E_f(\text{MeV})$	$2^-1, 1.951\text{MeV} \rightarrow$ $2^+1, g.s.$	$2^-0, 4.974\text{MeV} \rightarrow$ $2^+0, 1.97\text{MeV}$
life time (τ_-)	2.6 ± 0.3 ps	14 ± 5 ps
branching ratio (b_-)	60 %	4.0 ± 0.9 %
mixing ratio $(\delta_-)_{exp}$	(-0.10 ± 0.10) [31]	
mixing ratio $(\delta_-)_{theo}$	0.009	
$B(\text{E1})_{exp} (\text{e}^2 \text{fm}^2)$	$1.9 \cdot 10^{-5}$	$0.7 \cdot 10^{-7}$ (if $\delta_- = 0.0$)
$B(\text{E1})_{theo} (\text{e}^2 \text{fm}^2)$	0.008	
$B(\text{M2})_{exp} \mu_N^2 \text{fm}^2$	≤ 25	
$B(\text{M2})_{theo} \mu_N^2 \text{fm}^2$	2.5	0.24
$M_{PNC}^{DDH} (\text{eV})$	-0.019	0.122
$M_{PNC}^{DDH} (\text{eV}), h_\pi^1 = \frac{1}{4}(h_\pi^1)_{DDH}$	-0.057	0.122
$M_{PNC}^{KM} (\text{eV})$	-0.023	0.067

Table 1.

$h_{meson}^{\Delta T}$	KM	DDH	AH	DZ
h_{π}^1	0.19	4.54	2.09	1.30
h_{ρ}^0	-3.70	-11.40	-5.77	-8.30
h_{ρ}^1	-0.10	-0.19	-0.22	0.39
h_{rho}^2	-3.30	-9.50	-7.06	-6.70
$h_{\rho'}^1$	-2.20	0.00	0.00	0.00
h_{ω}^0	-1.40	-1.90	-4.97	-3.90
h_{ω}^1	-1.00	-1.10	-2.39	-2.20

Table 2.

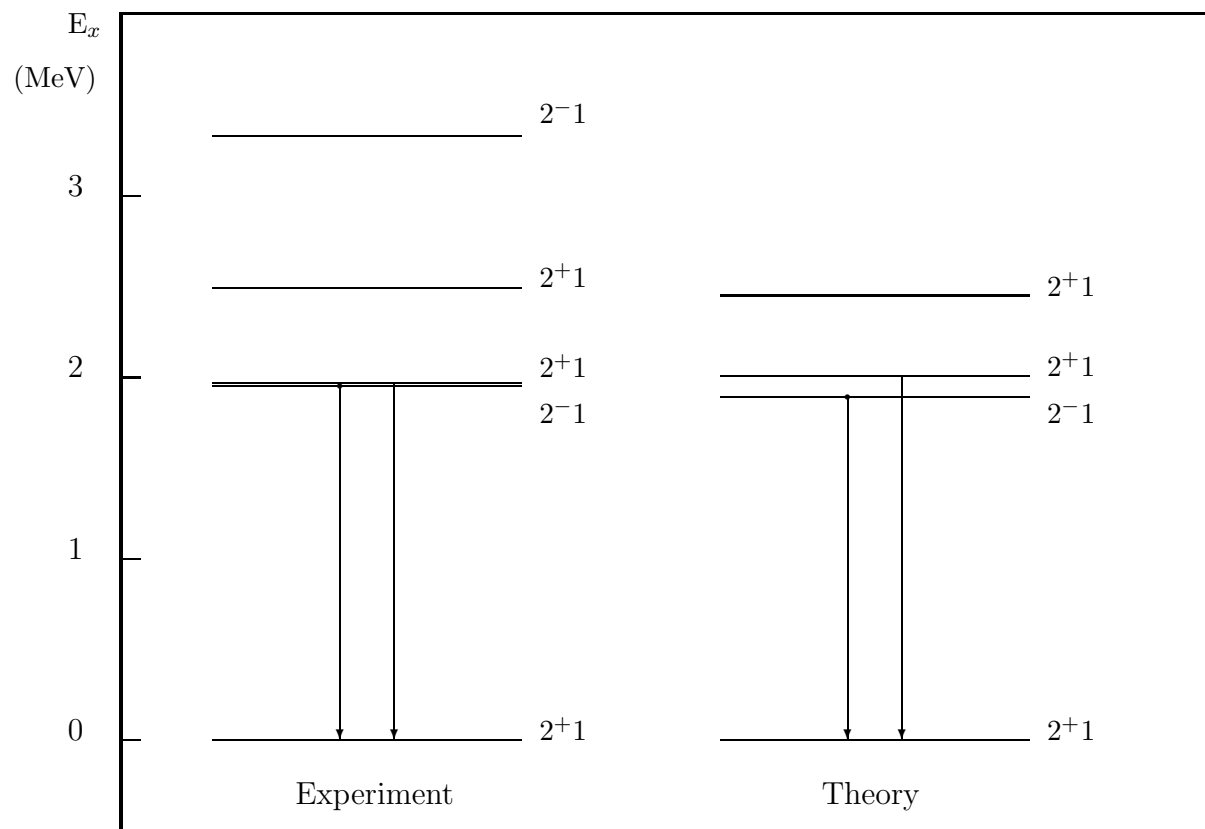


Figure 1.

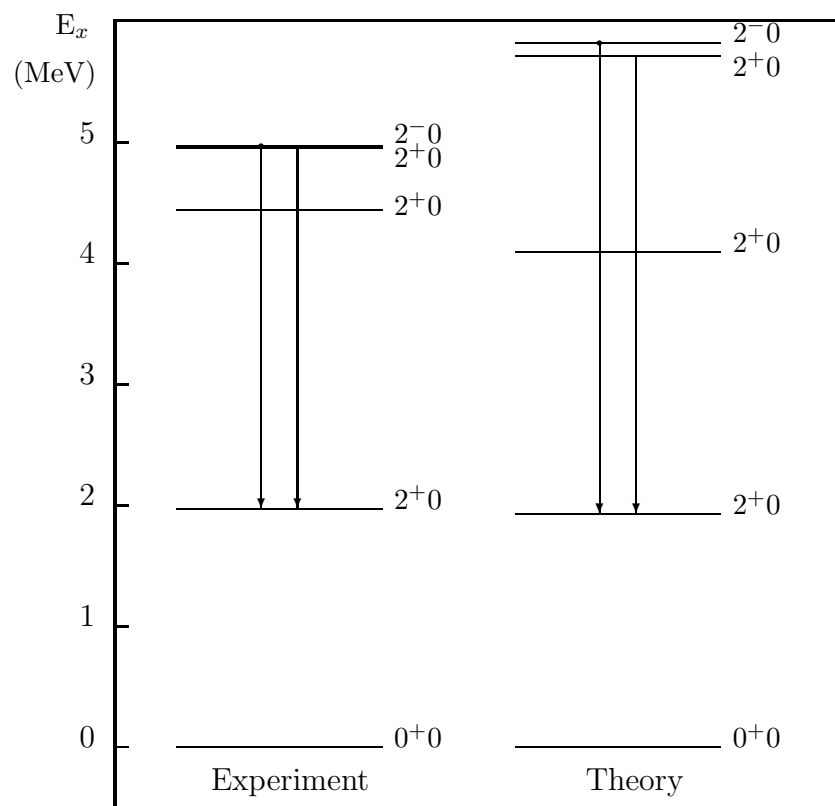


Figure 2.